USE OF HYDRO-GEOPHYSICS STREAMING POTENTIAL (SP) SIGNALS IN EVALUATING ENVIRONMENTAL FRIENDLY BIO-ECOLOGICAL DRAINAGE SYSTEM (BIOECODS^{TM}) EFFECTIVENESS

by

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Special Dedications to

My

Beloved Parents

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LIST OF ABBREVIATIONS

2-D	2-Dimensional Survey
3-D	3-Dimensional Survey
A.C.	Alternating Current
BIOECODS	Bio-Ecological Drainage System
D.C.	Direct Current
ERT	Electrical Resistivity Tomography
mm	millimeter
mV	millivolts
REDAC	River Engineering and Urban Drainage Research Centre
Sg. Kerian	Sungai Kerian
SP	Self-Potential
SPS	Seberang Prai Selatan
USM	Universiti Sains Malaysia

LIST OF SYMBOLS

°	Degree
°C	Degree Celsius
‘	Minutes
π	Pi
ζ	Zeta potential (V)
σ	Electrical conductivity (Sm^{-1})
C_1, C_2	Solution concentrations
C_E	Electro filtration coupling coefficeient
$CuSO_4$	Copper (II) Sulfate
δP	Pressure difference
ε	Dielectric constant of the pore fluid
ϵ_f	Dielectric permittivity (Fm^{-1})
E_d	Diffusion Potential
E_N	Nernst Potential
E_K	Electrokinetic potential as a result from an electrolyte flowing through a porous media
F	Electrical formation factor (dimensionless)
F_c	Faraday’s constant (96487 C mol^{-1})
g	Gravity (ms^{-2})
Hz	Hertz
I	Current
I_a, I_c	Mobilities of the anions (positive) and cations (negative)
η	Viscosity of the porefluid

η_f	Dynamic viscosity (Pa.s)
n	Number of electrons exchanged
N	Ionic valence
Ω	Ohm
θ_1, θ_2	Incident and refracted angles
P	Electrical resistivity of the pore fluid
P_f	Density ($kgms^{-1}$)
R, ρ	Resistivity
R_g	Universal gas content ($8.314 JK^{-1} mol^{-1}$)
$S\ m^{-1}$	Siemens per meter
T	Absolute temperatue (K)
V	Voltage
v_1, v_2	Material velocities

PENGGUNAAN ISYARAT HIDRO-GEOFIZIK KEUPAYAAN (SP) ALIRAN DALAM PENILAIAN KEBERKESANAN SISTEM SALIRAN MESRA ALAM BIOECODS^{TM}

ABSTRAK

Teknik keupayaan sendiri (SP) merupakan salah satu daripada kaedah hidrogeofizik tanpa-musnah (tidak melibatkan penggerudian dan pengorekan tanah) telah digunakan dalam penyiasatan air bawah permukaan bertujuan untuk menyediakan informasi berkaitan pengaliran air bawah tanah. Ujian lapangan dijalankan untuk menilai dan menganalisa sifat-sifat air bawah tanah seperti arah dan magnitud aliran serta corak anomalinya yang berasosiasi dengan sistem pengaliran BIOECODS^{TM} di sekitar Kampus Kejuruteraan, Universiti Sains Malaysia, Nibong Tebal yang dibangunkan oleh Pusat Penyelidikan Kejuruteraan Sungai dan Saliran Bandar, USM. Nilai anomali diperolehi berdasarkan ukuran terhadap perbezaan keupayaan yang wujud secara semulajadi yang terhasil daripada mekanisma elektrokimia, elektrokinetik ataupun termoelektrik, di mana arus hidraulik akan menjana arus elektrik bawah tanah (puluhan mV) melalui proses elektrokinetik. Keadaan semulajadi bagi nilai keupayaan sendiri di tiga kawasan yang telah dipilih diukur menggunakan sepasang elektrod Cu/$CuSO_4$ tak berkutub di seluruh kawasan. Anomali SP yang diperolehi seterusnya disemak silang menggunakan beberapa kaedah sokongan iaitu kajian keberintangan elektrik, kaedah seismos biasan dan data lubang gerudi untuk menganalisis sifat tanah permukaan serta aliran air bawah tanah di kawasan kajian di samping mengira kadar dan arah pergerakan air bawah tanah yang melalui akuifer. Dari keputusan yang diperolehi, anomali positif mewakili kehadiran aliran air di tempat kajian. Melalui survei yang telah dijalankan, anomali positif dari turutan 4 mV ke 35 mV mewakili kehadiran aliran air pada sub-permukaan dan berkait secara langsung dengan komponen BIOECOD^{TM} iaitu terusan. Sebarang perbezaan yang tidak ketara terhadap landskap serta keadaan ketinggian topografi menunjukkan nilai SP pertengahan, manakala kawasan yang kering boleh dikenalpasti melalui nilai SP yang jauh lebih rendah dan mempunyai kepolaran negatif pada tempat tertentu. Nilai-nilai keupayaan sendiri yang diukur pada titik-titik tertentu ini telah menunjukkan ketidakseragaman keadaan tanah dan

ia bergantung kepada keadaan topografi, keporosan, ketelapan serta kelembapan pada formasi tanah, ketepuan air dan perubahan cuaca harian di kawasan kajian. Bantuan kaedah pengimejan 2-D bagi kerintangan elektrik dan kajian seismos biasan untuk menentusahkan geologi dan keadaan sub-permukaan tanah bagi kajian hidrogeologi persekitaran juga dilakukan.

USE OF HYDRO-GEOPHYSICAL STREAMING POTENTIAL (SP) SIGNALS IN EVALUATING ENVIRONMENTAL FRIENDLY BIO-ECOLOGICAL DRAINAGE SYSTEM (BIOECODS^{TM}) EFFECTIVENESS

ABSTRACT

The Self-Potential (SP) technique is one of the non-invasive hydrogeophysical methods used in subsurface water investigation to provide information concerning near surface water flow. This study was carried out to evaluate and analyze the flow characteristics such as the direction and magnitude of water flows associated with the BIOECODS^{TM} drainage system within the Engineering Campus of Universiti Sains Malaysia (USM), Nibong Tebal. The SP values are obtained based on the measurement of naturally occurring potential differences generated mainly via electrochemical, electrokinetic and thermoelectric mechanisms, and the hydraulic currents that generate underground electrical currents (tens of mV) through electrokinetic process. The natures of streaming potential at three selected areas were measured using a pair of non-polarized $Cu/CuSO_4$ electrodes over the entire array. The SP anomalies were then cross-checked with electrical resistivity and seismic refraction supplementary survey and borehole data to analyze the upper soil characterization as well as to calculate the rate and direction of movement of groundwater through aquifers and confining units of the subsurface. Initial results show that general trends of positive anomalies represent the significance of subsurface water flow. The SP results show that the positive polarity anomalies in order of 4 mV to 35 mV represent the significance of subsurface water flow and were directly related to the BIOECODS^{TM} component, swale. Any depression landscapes over slightly elevated ground often show moderate SP voltages (value and polarity), whilst the dry spots were typified by the lower and occasionally negative polarity signatures in many places. These measured SP values at any particular points show an inconsistency and strongly depend on the landscape, porosity, permeability and moisture of soil formation, water saturation and the climatic daily variation of the studied area. The investigations were supported by auxiliary 2-D resistivity and seismic refraction imaging surveys to confirm the geology and condition of the subsurface of the study area.

CHAPTER 1

INTRODUCTION

1.1 Background

According to Ogilvy et al. (1969), Abaza and Clyde (1969), Bogoslovsky and Ogilvy (1970), Corwin and Hoover (1979), Sill (1983) and Yasukawa et al. (2005), it has been decades since streaming potential SP (infiltration) measurements have been used to study subsurface fluid flow for hydrological, geothermal and volcanics investigation. Indeed, hydraulic currents generate underground electrical currents (tens of mV) through electrokinetic process. Time variations in SP study allow to monitor water fluxes during infiltration (Doussan et al., 2002 and Darnet et al., 2004), ground water pumping (Darnet et al., 2003) or seepage (Titov et al., 2002).

Petiau (2000) proposed that SP signals can be mapped using non-polarizing electrodes placed in contact with the ground. These self-potential (SP) measurements can be related to ground water flow in unconfined aquifers (water-logged area) (Fournier, 1989; Birch, 1998 and Reynolds, 1997). It follows that preferential fluid flow pathways characterized by strong hydraulic transmissivities should have a typical electrical signature observable at the ground surface. Streaming potential monitoring is a low-cost technique that requires only electrodes connected to a data logger to make non-invasive measurements related to groundwater flow. Its sensitivity to water flow gives the SP method a distinct advantage compared with other non-invasive techniques. SP monitoring can efficiently detect seepage where other electrical and electromagnetic methods (except induced polarization) can only resolve geological structures (Buselli and Lu, 2001). It is a passive potential field technique and normally provides information about directions and intensities of shallow or near-surface water flow conditions. Electrokinetics potentials thought to be due to fluid flow parallel to a geologic boundary or the water table, at which the properties change abruptly (Corwin, 1990).

1.2 Concept of BIOECODS^{TM}

The increment of impermeable area due to urban development in Malaysia may change the natural hydrology and infiltration characteristics of the catchments area. Hence, new techniques of drainage system are needed in order to control quantity and quality of stormwater in new development area. Besides, urban stormwater runoff was identified as a major source of heavy metals and toxic organic elements (Niemczynowicz, 1999). Thus, the research collaboration between Department of Irrigation and Drainage, Malaysia, and University Sains Malaysia, has resulted in the implementation of Bio-Ecological Drainage System (BIOECODS^{TM}) in Engineering Campus, University of Science Malaysia (Khairul Rahmah Ayub et al., 2005), designed and constructed by River Engineering and Urban Drainage Research Centre, USM (REDAC).

BIOECODS^{TM} at the USM Engineering Campus is a pilot project that applies the surface water management train concept in Malaysia (Ab. Ghani et al., 2004). It is a drainage system that was designed to incorporate the concept of infiltration engineering, storage at source and flow retardation. BIOECODS consists of three components namely ecological swale called Type A, Type B and Type C respectively depending on the number of modules available underneath the swale and

Dry Ponds (Figure 1.1). Figure 1.2 illustrates the conceptual design flow chart of the BIOECODS^{TM} operation system followed by the third component known as Ecological Pond (Wetpond, Detention Pond, Constructed Wetland, Wading River and Recreational Pond) which is located at the downstream part (Mohd Sidek et al., 2004). Part of this storm water management approach objective is to stabilize the landform and erosion control, to enhance the surrounding landscape and to minimize nuisance flooding and environmental impact of runoff water on water quality.

Grassed swale or bio-ecological swale is a subsurface structure designed to take runoff infiltration and flow from previous and impermeable surface. The grassed swale is defined as grass earth channel combined with subsurface module which enclosed within a permeable geotextile. Grassed swale has the ability to reduce on-site peak flow rates by increasing the roughness of the channel and infiltration rates. These vegetated system functions are to treat and remove pollutants by means of sedimentations, filtration, and soil absorption and plant uptake from stormwater. The dry pond is a detention basin with the purpose to temporary store the stormwater runoff. This detention basin is designed to store the surface of 600mm of the excess rainfall and blend with surrounding landscape.

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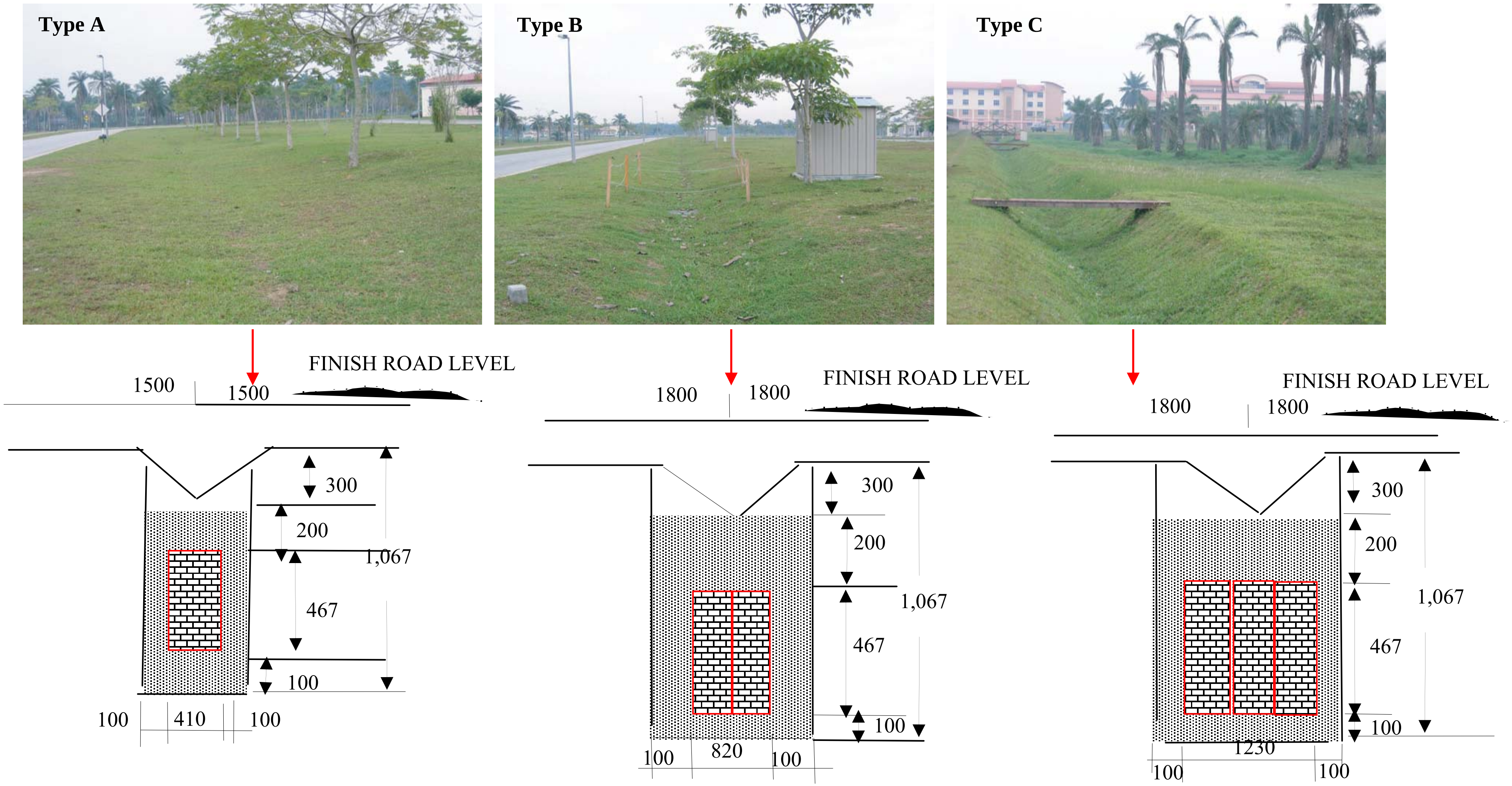

Figure 1.1 : Types of Bio-ecological swale. Type A, Type B and Type C depending on the number of modulus available underneath the swale (Khairul Rahmah Ayub et al., 2005).

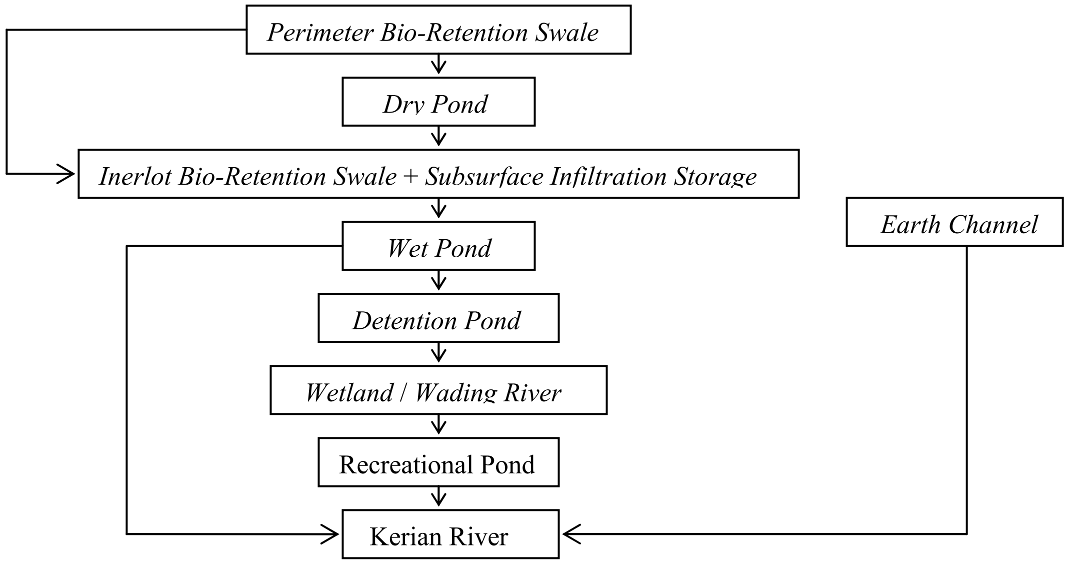

Figure 1.2 : Design concepts for BIOECODS^{TM} system developed for Engineering Campus, USM, Sri Ampangan (Khairul Rahmah Ayub et al., 2005).

1.3 Area Geomorphology

The study area is located in Mukim 9, district of Seberang Perai Selatan (SPS), Penang, Peninsular Malaysia. This area is bordered between latitudes 100° 29.5' and 100° 30.3' N and longitudes 5° 9.4' E and 5° 8.5' W (Figure 1.3). It is lowland and flat area, situated within the vicinity of Kerian River flood plain, which flowing into the Straits of Malacca. The campus was generally built over a previous palm oil estate, which is overlain by the recent Quaternary marine alluvial deposit and swampy in few places. These deposits are characterized by a thick sequence of soft to stiff, light grey to grey, sandy clay with numerous shell, and loose to medium dense, fine to coarse grained sand beds. Occurrence of coarse sand bar sequences marked the presence of Holocene ridge, an interesting geomorphologic feature of the area, indication of higher sea levels during 5000 years ago (Kamarudin, 1989). In order to raise the level of the area to 2-3 meters from existing level, the area was top-up with residual soil from nearby, highly weathered materials belong to Mesozoic granite and Permian sedimentary of Semanggol Formation. The filled soil is generally made-up of reddish, sandy clay soil (red-earth soil). Malaysian climate is equatorial (tropical) rainforest with an annual precipitation of 2500 to 3500 mm, potential evapotranspiration of 1130 mm m^{-1}, and the daily temperature of 28°C to 33°C (Hamdan and Burnham, 1996).

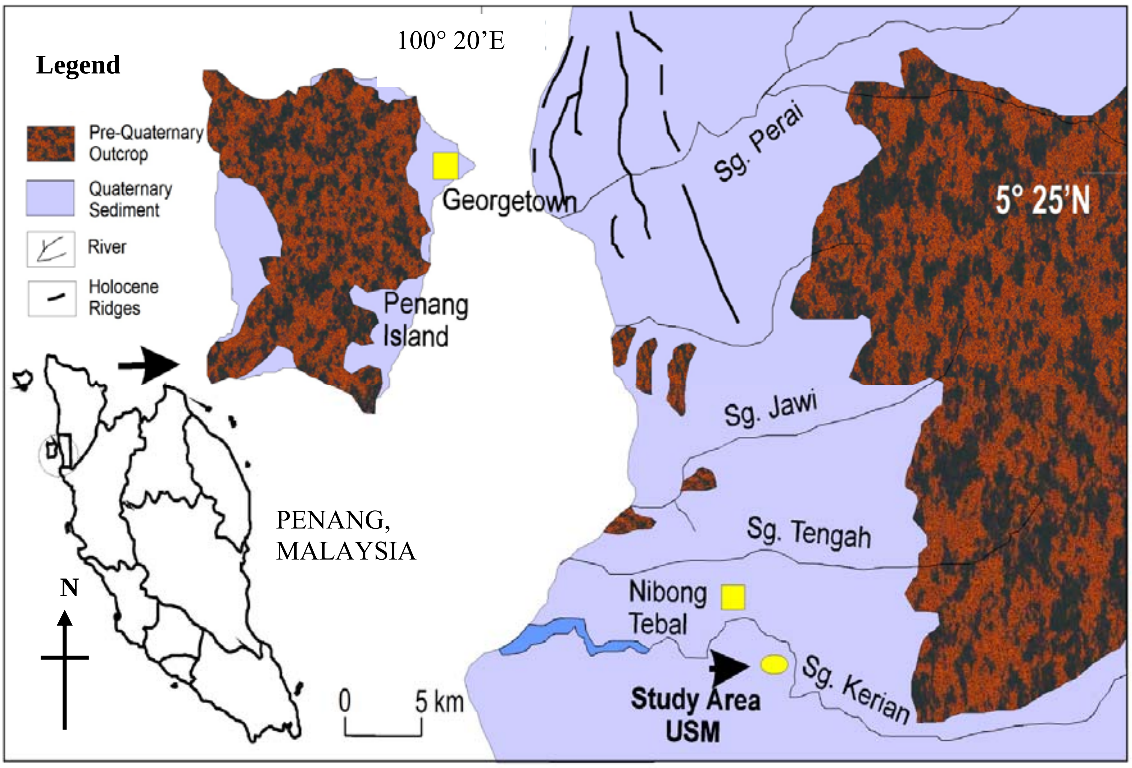

Figure 1.3 : Location and geology of the Seberang Perai Selatan (SPS) located within a low lying environment of Quaternary marine sediment of the Sg. Kerian flood plain system (Hamdan and Burnham, 1996).

1.4 Ground Water

The run-off of the precipitation waters from land to sea happens by 10% on the surface and by 90 % underground. Surface waters are constituted by rivers, springs, and lakes. Water-bearing underground zones are called aquifers, where water can be slowly moving or settled. Most groundwater originates from rainfall that has entered the earth (Sala, 2003). In the overburden aquifer, water fills the void space between grains of the soil. Bedrock aquifers underlie the surface soil (overburden) and overburden aquifers. In the bedrock aquifers, water occurs in fractures and other voids in the bedrock. Some types of bedrock such as sandstone may also have additional voids (intergranular voids) that are filled with groundwater. As in the case for subsurface water, groundwater flows from higher elevations or pressures toward lower elevations or lower pressures. Groundwater flow is usually toward a groundwater discharge area. Groundwater pressure, rather than elevation, controls the rate and direction of flow in confined aquifers. Those are aquifers that are isolated under impervious or poorly pervious strata (aquicludes and aquitards) (Donald, 2008). The passage of water through the surface of the ground is called infiltration and its downward movement to the saturated zone at depth is described as percolation. Water in the zone of saturated ground moves towards rivers, lakes and the seas and the process is known as ground water flow, where it is evaporated (Blyth et al., 1984). Smith (1990) stated that it is obvious that a soil's coefficient of permeability depends upon its porosity which itself related to the particle size distribution curve of soil such as gravel is much more permeable than clay. Table 1.1 indicates the typical values of permeability for granular and other materials.

Table 1.1 : Typical values of permeability for granular and other materials (Blyth et al., 1984)

Types of soil	**Permeability (m/s)**
Gravel	$>10^{-1}$ m/s
Sands	10^{-1} to 10^{-5} m/s
Fine sands, coarse silts	10^{-5} to 10^{-7} m/s
Silts	10^{-7} to 10^{-9} m/s
Clays	$<10^{-9}$ m/s

1.5 Problem statement

BIOECODS^{TM} developed for Engineering Campus, Universiti Sains Malaysia was generally built over a reclaimed area, which 2-3 m high covered top soil, underlained by previous palm oil estate area near to Sg. Kerian. The underground condition is characterized by occurrence of sandy clay and grained sand beds (obtained from borehole data) with high porosity and it stimulates water retention around study areas during heavy rainfall periods. Even supplementary methods such as seismic refraction survey and borehole were also carried out before but those methods are only able to provide information on the overburden stiffness and subsurface geological condition. Even though the depth of water table can be determined, such geophysical techniques were unable to provide the directions of underground water flow movement and occurrence of water stagnations. Thus, SP method which is rely on the streaming function of water to generate electrical signature is the best choice to be used in addressing issues related to the BIOECODS^{TM} performance investigation and to provide a tool and technology in monitoring the efficiency of BIOECODS^{TM} function. Other supplementary geophysical methods are still needed to support this investigation such as electrical resistivity and seismic survey are required especially in diagnose aspect and maintenance in future.

1.6 Research Objectives

The main objectives of this research are:

- To investigate the applicability of non-invasive geophysical self-potential (SP) and electrical resistivity techniques in the field of environmental engineering survey especially in the near surface groundwater movement associated with Bio-Ecological Drainage System.

- To investigate the effectiveness and workability of the BIOECODS components which play a major role in handling storm water run-off, especially grassed swale and dry pond components.
- To identify and analyst the distribution and streaming flow patterns of runoff water, saturated or non-saturated ground in relation to ground relief, soil nature (porosity) associated with these structures.
- To apply such finding that could provide reliable methods for BIOECODS^{TM} monitoring and maintenance in supporting effective storm water run-off management in near future.

1.7 Outline of the thesis

Chapter 2 highlights the background about self potential method, and this includes the anomalies, the mechanism, applications, technique in groundwater and environmental study and related algorithms. The usage of electrical resistivity survey, seismic survey and borehole data as supplementary methods in this research are also discussed here. Chapter 3 gives brief explanation about the equipments and methods used in this research. This chapter also describes the field procedure for self potential survey and electrical resistivity survey. In chapter 4, the data obtained from SP technique, electrical resistivity survey, seismic survey and borehole are presented and discussed. The corresponding results are compared to provide information about subsurface geology and other conditions. This particularly in identification of subsurface flow pattern anomaly and trends associated with BIOECODS^{TM} drainage system (components). Finally in chapter 5, conclusions for the research and findings are given and suggestions for a better future work are proposed, followed by references and appendices.

CHAPTER 2

Literature Review

2.1 Introduction

Water is essential to human's life, and the use of geophysics in determining the quantity and quality of groundwater has been pursued worldwide (Goldman, 2000). Nowadays the industrialization and urbanization in the river basin is rapid with large quantities of agricultural and ex-mining land being converted for urban use. The landscape for residential, commercial, industrial and institutional usage is transformed with the growing demand to spur the economy. However the extensive development causes a few environmental damages such as river basin being subjected to river over-bank floods, flash floods that afflict clogged drainage systems and river environment degradation. This issue has prompted the authority to come out with new concept in the planning and management of urban storm water runoff (Rozi Bin Abdullah et al., 2002). Thus, the research collaboration between Department of Irrigation and Drainage, Malaysia, and Universiti Sains Malaysia, has lead to the implementation of Bio-ecological Drainage System (BIOECODS^{TM}) in USM Engineering Campus as a pilot project for Malaysia. The construction of BIOECODS^{TM} which covers an area of 300 acres was completed at the end of December 2002 (Ab. Ghani et al., 2004; Zakaria et al., 2003).

The geophysical data is interpreted in many ways especially in 2-D and 3-D by applying geophysical modeling and inversion technique such as Self-Potential (SP) survey to visualize underground condition. Various geophysical techniques have been used in acquiring such data of self-potential, electrical resistivity tomography

(ERT) and seismic refraction information methods including borehole drilling. In many situations, SP method is widely used in the underground water flow and seepage studies apart for other application such as in mineral exploration and geothermal exploration.

2.2 Self Potential (SP)

Various electrical potentials are produced in native ground or within the subsurface altered by our actions, and it can be surveyed by both electrically or electromagnetically. SP (Spontaneous or Self Potential) refers to natural electrical potential differences that exist in the earth. It is first measured by Robert Fox in 1830 with copper plate electrodes connected to a galvanometer to measure an underground copper sulfide deposits in Cornwall, England (Reynolds, 1997). SP is a non invasive method (passive method) whereas no drilling or intrusion is required in order to obtain the data and its measurement usually involves natural occurring electrical potentials different between two points on the ground surface.

SP survey is normally applied in mineral exploration to detect conducted mineral deposits such as copper sulfide due to high oxidation and reduction potentials that occurs in the ore bodies' mineralization. Besides, the anomalies of SP are also contributed by the fluid flow in hydrogeology or the underground heat such in geothermal activities.

2.2.1 SP Anomalies

Self potential is a natural electrical potential existing within the earth which arises from a number of causes. These causes can be broadly classified into two groups (Neev and Yeatts, 1989):

i. Mineralization potentials, which are primarily the results of chemical concentration cells formed when conductive mineral deposits, such as graphite or sulfide, are intersected by the water table. Mineralization potentials have a constant value and almost always negative, and may have values up to several hundred millivolts.

ii. Background potentials, which are primarily a result of,
    (a) two electrolytes of different concentration being in contact with one another
    (b) electrolytes flowing through a capillary system or porous media
    (c) an electrolyte in contact with a solid
    (d) electromagnetically induced telluric currents

Background potentials can be either positive or negative, and usually have values of only a few tens of millivolts. The background potentials developed by electrolytes flowing through a capillary system, or porous media, called electro-filtration or streaming potentials, are used for the study of seepage. As water flows through a capillary system, it collects and transports positive ions from the surrounding materials. The SP anomalies and its sources are shown in Table 2.1. The positive ions accumulate at the exit point of the capillary, leaving a net positive charge. The untransported negative ions accumulate at the entry point of the capillary, thus leaving a net negative charge. If the streaming potentials developed by this process are of sufficient magnitude to measure, the entry point and the exit point of zones of concentrated seepage may be determined due to the negative and positive (respectively) self potential anomalies. As stated, it can be either positive or negative and usually have values of only a few tens of millivolts (Li et al., 1995; Revil et al., 1999; del Rio and Whitaker, 2001). Figure 2.1(a) indicates the type of self potential anomaly, in millivolts, that can be produced by an artesian water system, while Figure 2.1(b) presents the type of self potential anomaly that can be produced by groundwater draining or flowing into a fractured bedrock system. Self potential surveys have been successfully used to map reservoir leakage and water seepage paths through embankment and foundation materials (Davenport et al., 2008). The magnitude and polarity of self potentials will be affected by seepage flow (streaming potentials) and both lithological and structural factors.

Potentials resulting from seepage flow can generally be classified as:

i. Positive anomalies can represent subsurface water flow, and areas of water discharge.
ii. Negative anomalies can represent areas of water infiltration.

Potentials resulting from lithological and structural factors can generally be classified as (Davenport et al., 2008):

i. Positive anomalies can represent areas of a higher content of clayey material.
ii. Negative anomalies can represent zones of accumulations of coarse detritus material.
iii. A sudden change in the magnitude and/or sign of the anomaly can represent a geologic contact.
iv. Negative anomalies in a homogeneous rock formation can represent areas of fracturing.

It is evident that to separate streaming potentials from lithologic and structural potentials, care must be exercised in the field to note all soil and geological changes along each profile. In many cases, this information may be sufficient to eliminate certain factors from causing a self potential anomaly. For example, to determine if a negative anomaly is the result of water infiltration or fractured rock may be very difficult; however the geological position of the anomaly, its size and shape, observations of local outcrops, and correlation of the anomaly outcrops, and correlation of the anomaly with known subsurface geological conditions may all be factors that can be used to eliminate water infiltration as the cause of the anomaly.

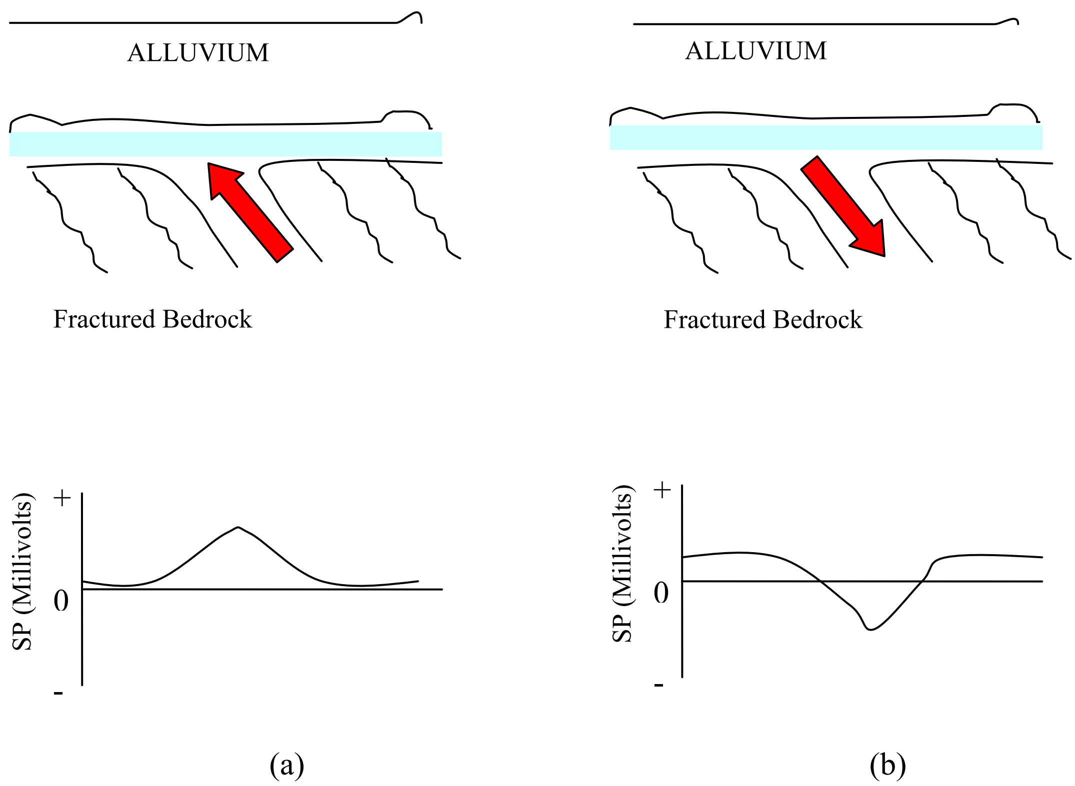

Figure 2.1 : (a) The type of self potential anomaly, in millivolts, that can be produced by an artesian water system and (b) The type of self potential anomaly that can be produced by groundwater draining or flowing into a fractured bedrock system (Davenport et al., 2008).

Table 2.1 : SP anomalies and its sources. Groundwater movement produces anomalies of either positive or negative 100-1000 mV (Reynolds, 1997).

Source	**SP Anomaly**
Mineral Potentials	
Sulphide or graphite ore bodies, magnetite and other electronically conducting minerals, coals,manganese	Negative : 100 – 1000 mV
Quartz veins, pegmatites	Positive : 10 – 100 mV
Background Potentials	
Fluid streaming, geochemical reactions	Positive / negative : < 100 mV
Bioelectric effects from plants, trees	Negative : < 300 mV
Groundwater movement	Positive / negative : 100 – 1000 mV
Topography	Negative : up to 2000 mV

2.2.2 Mechanism of Self Potential

Field studies indicate that the causative body must lie partially in a zone of oxidation for an SP anomaly to occur. A widely accepted mechanism of SP (Sato & Mooney, 1960; Kilty, 1984) requires the causative body to straddle the water table. Below the water table electrolytes in the pore fluids undergo oxidation and release electrons which are conducted upwards through the ore body. At the top of the body the released electrons cause reduction of the electrolytes. A circuit thus exists in which current is carried electrolitically in the pore fluids and electronically in the body so that the top of the body acts as a negative terminal. This explains the negative SP anomalies that are invariably observed and also their stability as the ore body itself undergoes no chemical reactions and merely serves to transport electrons from depth. The SP values that occur underground normally are caused by electrochemical process or mechanical activities, and groundwater is the common factor in all processes that generate self potentials. It acts as an electrolyte or a solvent. Electrics are drained through the rocks via three mechanisms that are dielectrics, electrolytic and electronics. Electrical conductivity (σ) of porous rocks depends on the porosity and movement of water or other fluid to pass through it. SP are produced by a number of mechanisms (Reynolds, 1997):

A. Mineral potential

The mineral potential results from a combination of contact electrode and electrochemical potentials, and is associated with some mineral deposits. The electrode contact potential is a potential difference between two dissimilar metal electrodes immersed in a homogenous solution. Mineral potential refers to the ores that conduct electronically such as most sulfide ores, not sphalerite (zinc sulphide) magnetite and graphite. Large potentials observed over certain ore bodies containing good electronic conductors such as pyrite or graphite are too large to be explained by electrochemical effects alone. Sato and Mooney (1960) proposed an SP mechanism in pyrite ore bodies (Figure 2.2) and explained that large mineral potentials that occur at where ore body straddles water table may be due to oxidation or reduction reactions above/below water table. Above water table, ions in surrounding electrolyte are chemically reduced, which means they gain electrons while below water table the ions are oxidized (lose electrons). The sulphide ore body allows electrons to move from below to above the water table by electronic conduction through the ore body. That makes the flow of electrons leaves the upper part of the ore body with a net negative charge, while the lower part are left with a net positive charge.

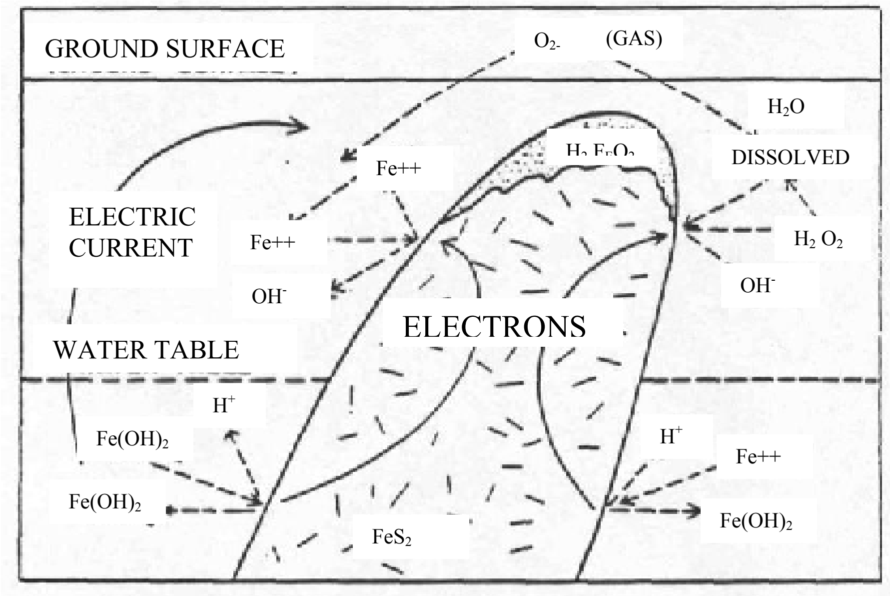

Figure 2.2 : Proposed electrochemical mechanism for self potential (Sato and Mooney, 1960).

B. Electrochemical potential

(i) Diffusion Potential

Diffusion potential is also known as liquid junction potential. It is a potential difference across the boundary between electrolytic solutions with different compositions. Diffusion potentials (~10 mVs) can arise from differences in mobilities of electrolytes with different concentrations in groundwater. There must be a mechanism to maintain imbalance in the electrolytic concentrations otherwise diffusion of ions will remove any potential gradient.

$$E_K = \frac{-R_g T(I_a - I_c)}{nF_c(I_a + I_c)} \ln(C_1/C_2) \qquad (2.1)$$

Where :

I_a, I_c = mobilities of the anions (positive) and cations (negative)

R_g = universal gas content ($8.314 JK^{-1}\ mol^{-1}$)

T = absolute temperatue (K)

N = ionic valence

F_c = Faraday's constant (96487 C mol^{-1})

C_1, C_2 = solution concentrations

(ii) Nernst potential

Nernst equation describes potential of electrochemical call as a function of concentrations of ions taking part in the reaction. It is created by different ion concentrations at electrodes in example; when two identical electrodes are immersed in a homogenous solution, there is no potential difference obtained between them but if the concentrations of solutions are different at the two electrodes, then a potential difference will exist.

$$E_n = -\frac{RT}{nF}\ln(C1/C2) \tag{2.2}$$

Where :

$I_a = I_c$ in the diffusion potential equation.

(C1/C2) = reaction quotient

n = number of electrons exchanged

RT/F = constant temperature value

C. Electrokinetic (Streaming) Potentials

Electrokinetic potential E_K is created when an electrolyte flows through a capillary or a porous medium. The flow of electric currents is related to hydraulic gradient and physical or electrical properties of electrolyte and pores. Electrokinetic potentials thought to be due to fluid flow parallel to a geologic boundary or the water table, at which the properties change abruptly as shown in Figure 2.3.

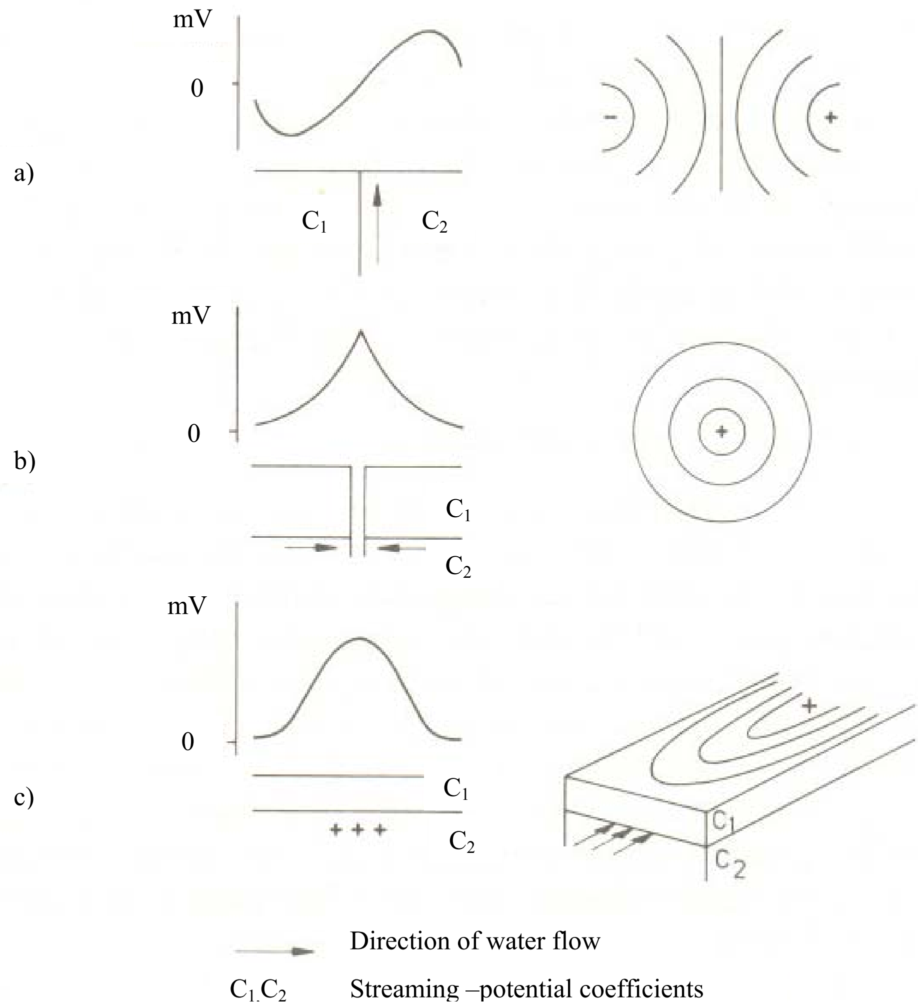

Figure 2.3 : SP electrokinetic flow models (Schiavone et al., 1984) (a) flow along fault (b) groundwater pumping (c) flow along water table.

Electrokinetic potentials tend to become more positive in the direction of fluid flow, which is opposite to the flow of negative charge. Electrokinetic anomalies are usually associated with the factor such as topography whereas negative charge tends to flow uphill as water flows downhill. This can be supported by the values that has been reported at the peak of Adak Volcano in Alaska (-2693 mV) and on a mountain in Peru (-1842 mV). However the topographic effect requires correction where slope angle exceed 20°. Other factors are heavy rainfall as where SP anomalies of the order of 5 mV can be produced as the water from heavy rainfall percolates through the soil; and groundwater pumping which can produced the SP anomalies of ~10s mV as shown in Figure 2.4 (Reynolds, 1997).

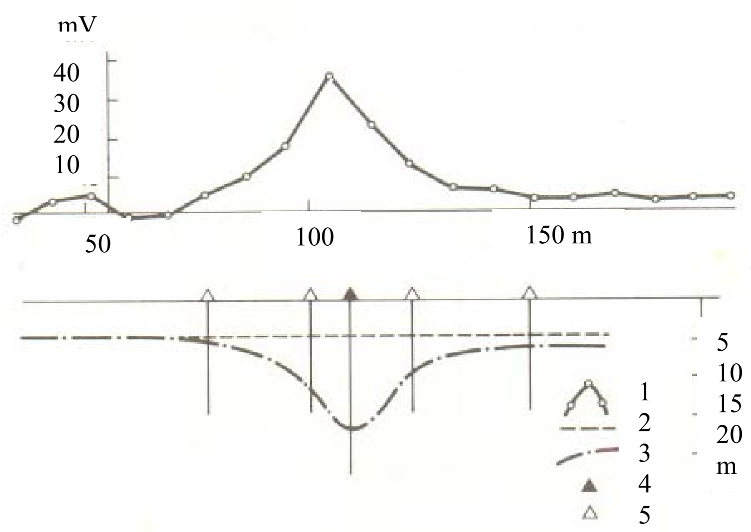

Figure 2.4 : SP anomalies produced by groundwater pumping (Semenov, 1980). (1) measured SP; (2) groundwater level before pumping (3) groundwater level during pumping; (4) boreholes for pumping; (5) piezometric boreholes.

The potential, E per unit of pressure drop P (the streaming potentials coupling coefficient) is given by:

$$E_K = \frac{-\varepsilon \rho C_E \delta P}{4\pi\eta} \tag{2.3}$$

Where:

P = electrical resistivity of the pore fluid

E_K = electrokinetic potential as a result from an electrolyte flowing through a porous media

ε = dielectric constant of the pore fluid

η = viscosity of the porefluid

δP = pressure difference

C_E = electro filtration coupling coefficeient

2.2.3 SP Applications

Self-potential (SP) prospecting is one of the oldest geoelectrical methods and it is still used in many fields of applied geophysics (Patella, 1997). A wealth of interesting case histories are reported in the literature concerning mining (Corry, 1985), hydrogeological (Bogoslovsky et al., 1974), geothermal (Zohdy et al., 1973) and archaeological surveying (Wynn et al., 1984) as well as in engineering geophysics for landslide (Bogoslovsky et al., 1977) and dam and embankment seepage control (Butler, 1984). In recent years there has also been a renewal of interest in the study of tectonic processes using the SP method, especially for forecasting earthquakes (Corwin et al., 1977) and volcanic eruptions (Di Maio et al., 1994).

A. Archeological Surveying

In the archaeological prospection, the self-potential method is very rarely used because related phenomena are not very well known and there are many important measuring problems. The main problem in this method occurs in the physical and chemical changes within the measuring media and the non-polarizable electrodes which are used during the data acqusition. As known, the inner polarization difference of non-polarizable electrodes changes with time and other unknown factors. This phenomenon is observed as a noise during the data collection process. However, all of these undesired factors can be eliminated by an appropriate measuring system. Thus, measuring process should be rather improved compare to classical data collection techniques (Drahor, 1993; Drahor et al., 1996; Wynn et al., 1984).